Wings In Orbit

Scientific and Engineering Legacies of the Space Shuttle

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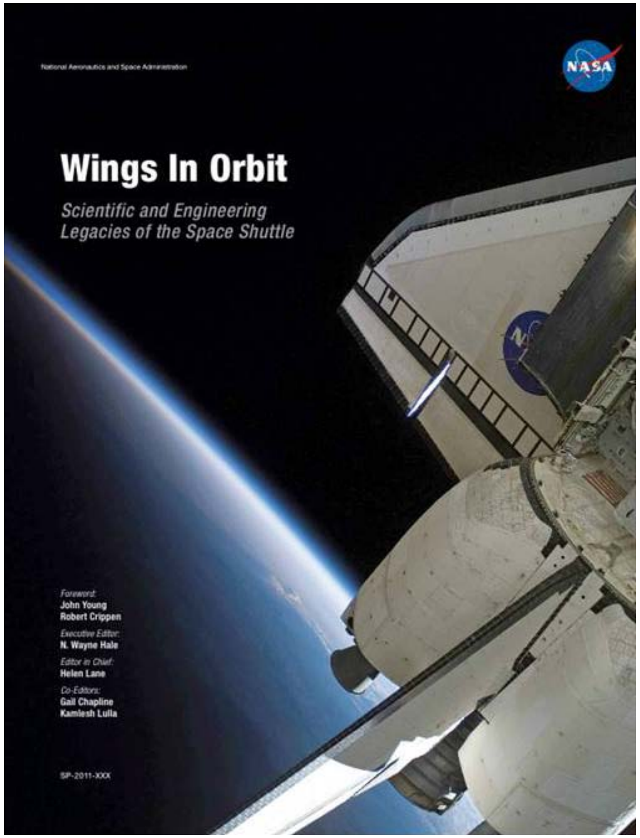

An agency-wide Space Shuttle book project involving contributions from all NASA centers

Space Shuttle book: September 2010

Vision

Overall vision for the book:

The "so what" factor?

Our vision is to "inform" the American people about the accomplishments of the Space Shuttle and to "empower" them with the knowledge about the longest-operating human spaceflight program and make them feel "proud" about nation's investment in science and technology that led to Space Shuttle Program accomplishments.

Vision *(continued)*

Focus:

- Science and Engineering accomplishments
  (not history or hardware or mission activities or crew activities)
- Audience: American public with interest in science and technology
  (e.g., Scientific American *Readership: a chemical engineer, a science teacher, a physician, etc.)*

Definition of Accomplishment:

- Space Shuttle Program accomplishments are those “technical results, developments, and innovations that will shape future space programs” or “have affected the direction of science or engineering” with a focus on unique contributions from the **shuttle as a platform**.

Guiding Principles:

- Honest
- Technically correct
- Capture the passion of the NASA team that worked on the program

Wings In Orbit

A new, authentic and authoritative book written by the people of the Space Shuttle Program

- **The Historical Legacy**
- **The Shuttle and its Operations**
- **Engineering Innovations**
- **Major Science discoveries**
- **Social, Cultural, and Educational Legacies**
- **Commercial Aerospace Industries and Spin-offs**
- **The Shuttle Continuum, Role of Human Spaceflight**

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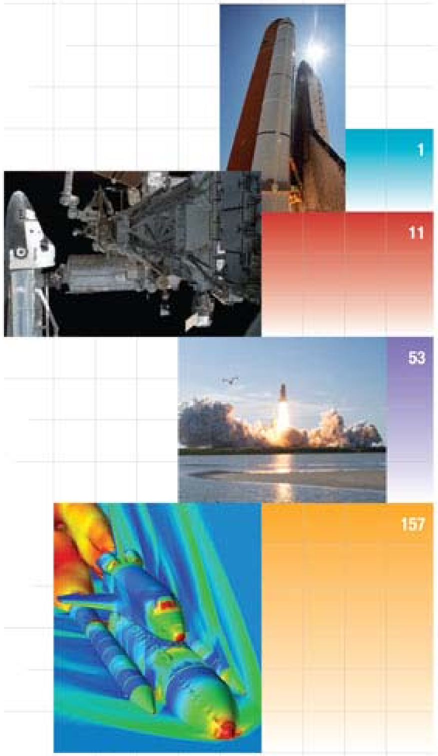
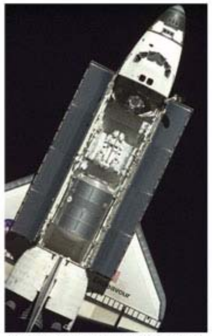




Raffaello, the Italian logistics module, flies in the payload bay on STS-100 in 2001.

The Raffaello was successfully berthed and the mission went smoothly until a software glitch in the evolving ISS computer architecture brought all ISS communications to a halt, along with the capability of the ground to command and control the station. Coordinating through the shuttle's communications systems, the station, shuttle, and ground personnel organized a dramatic restart of the ISS.

A major control computer was rebuilt using a payload computer's hard drive, while the heartbeat of the station was maintained by a tiny piece of rescue software—appropriately called "Mighty Mouse"—in the lowest-level computer on the massive spacecraft. Astronaut Susan Helms directly commanded the ISS core computers through a notebook computer. That job was normally assigned to Mission Control. Having rescued the ISS computer architecture, the ISS crew inaugurated the new Space Station Remote Manipulator System by using it to return its own delivery pallet to Endeavour's cargo bay. Through a mix of intravehicular activity, EVA, and robotic techniques shared across four space agencies, the ISS and Endeavour each ended the ambitious mission more capable than ever.

STS-120—Dramatic Accomplishments

By 2007, with the launch of STS-120, the ISS construction was in its final stages. Crew members encountered huge EVA tasks in several previous flights, usually dealing with further problems in balky ISS solar arrays. A severe Russian computer issue had occurred during flight STS-117 in June of that year, forcing an international problem resolution team to spring into action while the shuttle took over the attitude control of the station.

STS-120, however, was to be one for the history books. It was already historic in that by pure coincidence both the shuttle and the station were commanded by women. Pamela Melroy commanded Space Shuttle Discovery and Peggy Whitson commanded the ISS. Further, the Harmony connecting node would need to be relocated during the stage in a "must succeed" EVA. During that EVA, the ISS would briefly be in an interim configuration where the shuttle could not dock to the ISS. On this flight, the ISS would finally achieve the full complement of solar arrays and reach its full width.

Shortly after the shuttle docked, the ISS main array joint on the starboard side exhibited a problem, which was traced to crushed metal grit from improperly treated bearing surfaces that fouled the whole mechanism. While teams worked to re-plan the mission to clean and lubricate this critical joint, a worse problem came up. The outermost solar array ripped while it was being deployed. The wing could not be retracted or further deployed without greater damage. It would be destroyed if the shuttle tried to leave. The huge Space Station Remote Manipulator System could not reach the distant tear, and crews could not safely climb on the 160-volt array to reach the tear.

In an overnight miracle of cooperation, skill, and ingenuity, ISS and shuttle engineers developed a plan to extend the Space Station Remote Manipulator System's reach using the Orbiter Boom Sensor System with an EVA astronaut on the end. The use of the boom on the shuttle's arm for contingency EVA had

Astronaut Pamela Melroy (left), STS-120 (2007) commander, and Peggy Whitson, Expedition 16 commander, pose for a photo in the Pressurized Mating Adapter of the International Space Station as the shuttle crew members exit the station to board Discovery for their return trip home.

The Shuttle and its Operations

October 2010) over a period of 29 years, the Orbiter deployed a multitude of satellites for Earth observation and telecommunications, interplanetary probes such as Galileo/Jupiter spacecraft, Magellan/Venus Radar Mapper, great observatories that included the Hubble Space Telescope, Compton Gamma Ray Observatory, and Chandra X-ray Observatory. The Orbiter even functioned as a science platform/laboratory; e.g., Spacelab, Astronomy Ultraviolet Telescope, US Microgravity Laboratory, US Microgravity Payload, etc. Aside from the experiments and satellite deployments that the shuttle performed, the most important accomplishment was the delivery and assembly of the ISS.

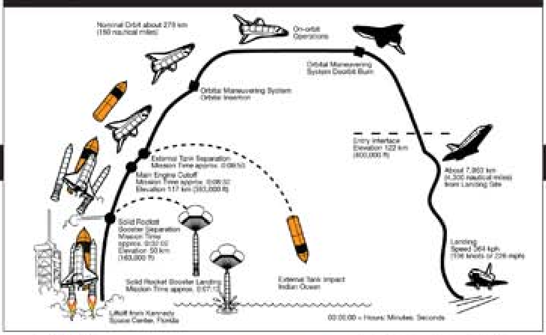
Space Shuttle Reusability

All components of the Space Shuttle vehicle, except for the ET, were designed to be reusable, flight after flight. The ET, once jettisoned from the Orbiter, fell to Earth where atmospheric heating caused the tank to break up over the ocean.

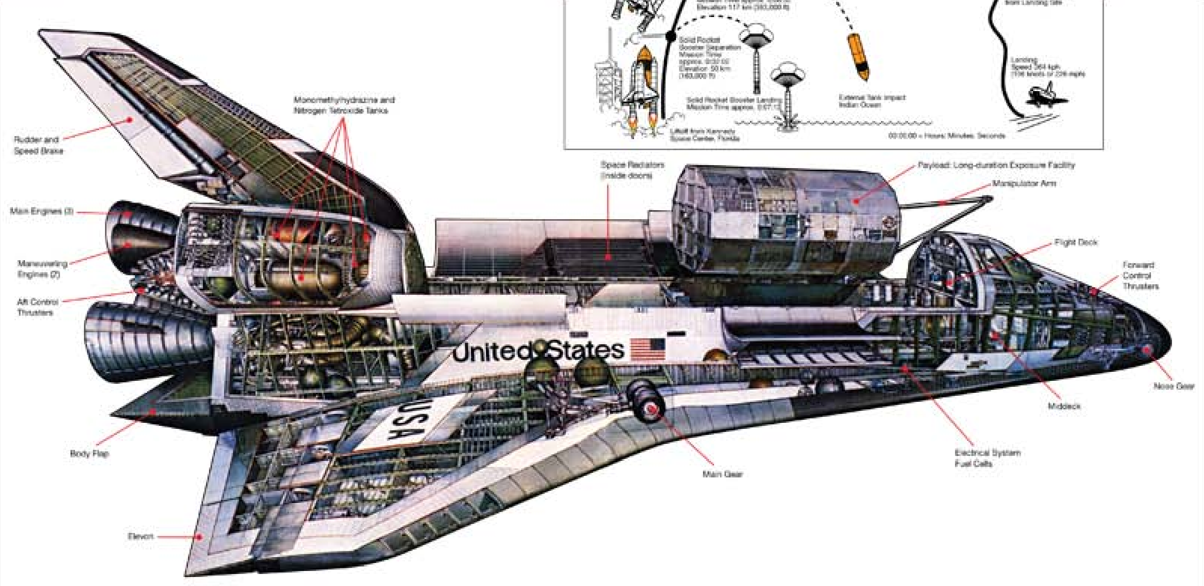
The SRBs, once jettisoned from the tank, parachuted back to the ocean where they were recovered by special ships and brought back to KSC. With their solid propellant spent, the boosters were de-stacked and shipped back to aerospace and defense company Thiokol—now ATK—in Utah for refurbishment and re-use. After every mission, the SRBs were thoroughly inspected to ensure that the components were not damaged and could be refurbished for another flight. Any damage found was either repaired, or the component was discarded.

The Orbiter was the only fully reusable component of the shuttle system. Each Orbiter was designed and certified for 100 space missions and required about 5 months, once it landed, to service the different systems and configure the payload bay to support the requirements for its next mission. NASA replaced the components only when they sustained a system failure and could not be repaired. Even though certified for 100 missions, Discovery, Atlantis, and Endeavour completed 39, 32, and 25 missions, respectively, by the end of the program. Challenger flew 10 missions and Columbia flew 28 missions before their loss on January 28, 1986, and February 1, 2003, respectively.

Typical Flight Profile



The Orbiter



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Engineering Innovations
Major Scientific Discoveries

Orbiter Thermal Protection System

Throughout the design and development of the Space Shuttle orbiter thermal protection system, NASA overcame many technical challenges to attain a reusable system that could withstand the high temperature environments of re-entry into Earth's atmosphere. Theodore von Karman, the dean of American aerodynamicists, wrote in 1956, "Re-entry is perhaps one of the most difficult problems one can imagine. It is certainly a problem that constitutes a challenge to the best brains working in these domains of modern aerophysics." He was referring to protecting the intercontinental ballistic missile nose cones. Fifteen years later, the Space Shuttle offered considerably greater difficulties. It was vastly larger. Its thermal protection had to be reusable, and this thermal shield demanded both light weight and low cost. The requirement for a fully reusable system meant that new thermal protection materials would have to be developed, as the ablative technology from the previous Mercury, Gemini, and Apollo Programs were only single-mission capable.

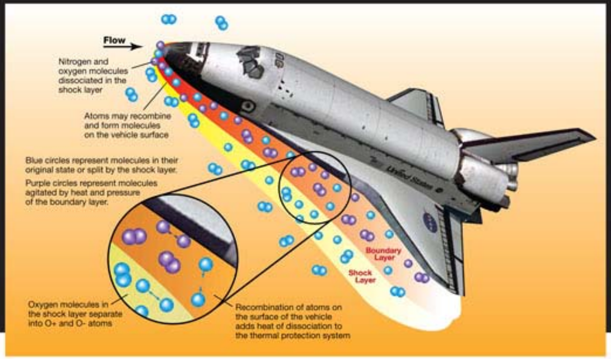
Engineers embraced this challenge by developing rigid silica/alumina fibrous materials that could meet the majority of heating environments on windward surfaces of the orbiter. On the nose cap and wing leading edge, however, the heating was even more extreme. In response, a coated carbon-carbon composite material was developed to

Thermal Protection System Could take the Heat

Shuttle Remained Protected During Catalytic Heating

While the re-entry surface heating of the orbiter was predominantly convective, sufficient energy in the shock layer dissociated air molecules and provided the potential for additional heating. As the air molecules broke apart and collided with the surface of the vehicle, they recombined in an exothermic reaction. Since the surface acted as a catalyst, it was important that the interfacing material/coating have a low propensity to augment the reaction.

Atomic recombination influenced NASA's selection of glass-type materials, which have low catalycity and allowed the surface of the orbiter to reject a majority of the chemical energy. Engineers performed precise arc jet measurements to quantify this effect over a range of surface temperatures for both oxygen and nitrogen recombination. This resulted in improved confidence in the thermal protection system.



bar code. With the use of a handheld scanning device, crew members simply scanned the empty food packages after meals. The device automatically recorded meal composition and time of consumption. Not only did bar codes facilitate science, they also had the additional benefit of supporting the Hazard Analysis and Critical Control Point program for space food.

Hazard Analysis and Critical Control Point is a food safety program developed for NASA's early space food system. Having a unique bar code on each food package made it easy to scan the food packages as they were stowed into the food containers prior to launch. The unique bar code could be traced to a specific lot of food. That served as a critical control point in the event of a problem with a food product. If a problem had arisen, the bar code data collected during the scanning could have been used to locate every package of food from that same lot, making traceability much easier and more reliable. This system of bar coding food items carried over into the ISS food system.

Food preparation equipment also evolved during the shuttle era. The earliest shuttles flew with a portable water dispenser and a suitcase-sized food warmer. The first version of the portable water dispenser did not measure, heat, or chill water, but it did allow the crew to inject water into foods and beverages that required it. This dispenser was eventually replaced by a galley that, in addition to measuring and injecting water, chilled and heated it, as well. The shuttle galley also included an oven for warming foods to serving temperature. Ironically, the food preparation system in use on the ISS does not include chilled water and, once again, involves the use of the suitcase-sized food warmer for heating US food products.

On STS-122 (2007), Astronaut Leland Melvin enjoys his dessert of rehydrated peach ambrosia. Also shown is the pair of scissors that are needed to open the pouch. On the pouch is a bar code that is used to track the food. The blue Velcro allows the food to be attached to the walls.

Food packaging for shuttle foods also changed during the course of the program. The original rigid, rectangular plastic containers for rehydratable foods and beverages were replaced by flexible packages that took up less room in storage and in the trash. The increase in crew size and mission duration that occurred during the program necessitated this change. These improvements continue to benefit the ISS food system.

Environmental

Environmental Conditions

Maintaining a Healthy Environment During Spaceflight

The shuttle crew compartment felt like an air-conditioned room to astronauts living and working in space, and the Environmental Control and Life Support System created that habitable environment. In fact, this system consisted of a network of systems that interacted to create such an environment, in addition to cooling or heating various Orbiter systems or components. The network included air revitalization, water coolant loop, active thermal control, atmosphere revitalization pressure control, management of supply and waste water, and waste collection.

The air revitalization system assured the safety of the air supply by using lithium hydroxide to maintain carbon dioxide and carbon monoxide at nontoxic levels. It also removed odors and trace contaminants through active charcoal, provided ventilation in the crew compartment via a network of fans and ducting, controlled the cabin's relative humidity (30% to 75%) and temperature (18°C [65°F] to 27°C [80°F]) through cabin heat exchangers for additional comfort, and supplied air cooling to various flight deck and middeck electronic avionics, in addition to the crew compartment.

Major Scientific Discoveries
Social, Cultural, and Educational Legacies

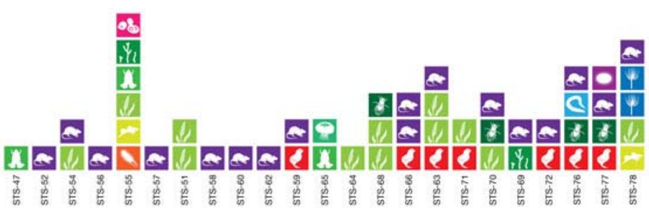
Bacteria More Dangerous in Space Environment

As reported by Cheryl Nickerson, the interplay between the human immune system and the invading microorganism determines if infection and disease occur. Factors that diminish immune capability or increase the virulence of the microorganism will greatly increase the likelihood of disease.

To gain insight to this issue, investigators compared responses of the food-borne bacterial pathogen *Salmonella typhimurium*, grown in the microgravity of spaceflight, to otherwise identical ground-based control cultures. Interestingly, they found that the spaceflight environment profoundly changed the gene expression and virulence characteristics (disease-causing potential) of the pathogen in novel ways that are not observed when growing the cells with traditional culture methods. This work also identified a "master molecular switch" that appears to regulate many of the central responses of *Salmonella* to the spaceflight environment.

On both the STS-115 (2006) and STS-123 (2008) shuttle missions, scientists investigated the spaceflight response of *Salmonella* grown in various growth media containing different concentrations of five critical ions. The effects of media ion composition on the disease-causing potential of *Salmonella* were dramatic. Flight cultures grown in media containing lower levels of the ions displayed a significant increase in virulence as compared to ground control cultures, whereas flight cultures grown in higher ion levels did not show an increase in virulence. The wealth of knowledge gained from these *Salmonella* gene expression and virulence studies provides unique insight into both the prevention of infectious disease during a spaceflight mission and the development of vaccines and therapeutics against infectious agents on Earth.

Astronaut Heidemarie Stefanyshyn-Piper, in the middeck of the Space Shuttle Atlantis, activates the MICROBE experiment, which investigated changes to Salmonella virulence after growth in space.



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Social Impact—NASA Reflects America's Changing Opportunities

Before the Space Shuttle was conceived, the aerospace industry, NASA employees, and university researchers worked furiously on the early human spaceflight programs to achieve President John Kennedy's goal of landing a man on the moon by the end of the 1960s. Although these programs employed thousands across the United States, white men overwhelmingly composed the aerospace field at that time, and very few women and minorities worked as engineers or scientists on this project. When they did work at one of NASA's centers, women overwhelmingly served in clerical positions, and minorities accepted low-paying, menial jobs. Few held management or professional positions, and none were in the Astronaut Corps, even though four women had applied for the 1965 astronaut class. By the end of the decade, NASA offered few positions to qualified minorities and women. Only eight blacks at Marshall Space Flight Center in Alabama held professional-rated positions while the Manned Spacecraft Center (currently known as Johnson Space Center) in Texas had 21, and Kennedy Space Center in Florida had only five.

Signs of change appeared on the horizon as federal legislation addressed many of the inequalities faced by women and minorities in the workplace. During the Kennedy years, the president ordered the chairman of the US Civil Service Commission to ensure that the federal government offered positions not on the basis of sex, but rather on a person's merit. Later, he signed into law the Equal Pay Act of 1963, making it illegal for employers to pay women lower wages than those paid to men for doing the same work. President Lyndon Johnson signed the Civil Rights Act of 1964, which prohibited employment discrimination (hiring, promoting, or firing) on the basis of race, sex, color, religion, or national origin; Title VII of the act established the Equal Employment Opportunity Commission, which executed the law. The Equal Employment Opportunity Act of 1972 strengthened the commission and expanded its jurisdiction to local, state, and federal governments during President Richard Nixon's administration. The law also required federal agencies to implement affirmative action programs to address issues of inequality in hiring and promotion practices.

One year earlier, NASA appointed Ruth Bates Harris as director of Equal Employment Opportunity. In the fall

Changing Faces of the Astronauts From 1985 Through 2010

In 1985, STS-51F—Center: Story Musgrave, MD, mission specialist, medical doctor. To Musgrave's right, and going clockwise: Anthony England, PhD, mission specialist, geophysicist; Karl Henize, PhD, mission specialist, astronomer; Roy Bridges, pilot, US Air Force (USAF); Loren Acton, PhD, industry payload specialist; John-David Bartoe, PhD, Navy payload specialist; Gordon Fullerton, commander, USAF.

In 2010, STS-131 and International Space Station (ISS) Expedition 23—Clockwise from lower right: Stephanie Wilson, mission specialist, aerospace engineer; Tracy Caldwell Dyson, PhD, ISS Expedition 23 flight engineer, chemist; Dorothy Metcalf-Lindenburger, mission specialist, high school science teacher and coach; Naoko Yamazaki, Japanese astronaut, aerospace engineer.

Social, Cultural, and Educational Legacies

Astronaut Guion Bluford conducting research on STS-53.

Guion Bluford, PhD
Colonel, US Air Force (retired). Astronaut on STS-8 (1983), STS-61A (1985), STS-39 (1991), and STS-53 (1992).

In 1983, Colonel Guion Bluford became the first African American to fly in space. He earned a Bachelor of Science in aerospace engineering from Pennsylvania State University, followed by flight school and military service as a jet pilot in Vietnam, which included missions over North Vietnam. He went on to earn a Master of Science and Doctor of Philosophy in aerospace engineering with a minor in laser physics from the Air Force Institute of Technology. He also earned a Master of Business Administration after joining NASA. Prior to joining NASA as an Air Force astronaut, he completed research with several publications. Since leaving NASA, he has held many leadership positions.

As a NASA astronaut, he flew on four missions: two on Challenger (1983, 1985), and two on Discovery (1991, 1992).

Dr. Bluford has said, "I was very proud to have served in the astronaut program and to have participated on four very successful Space Shuttle flights. I also felt very privileged to have been a role model for many youngsters, including African American kids, who aspired to be scientists, engineers, and astronauts in this country. For me, being a NASA astronaut was a great experience for which I will always cherish."

of 1973, Harris proclaimed NASA's equal employment opportunity program "a near-total failure." Among other things, the agency's record on recruiting and hiring women and minorities was inadequate. In October, NASA Administrator James Fletcher fired Harris, and Congress held hearings to investigate the agency's affirmative action programs. Legislators concluded that NASA had a pattern of discriminating against these groups. Eventually, a resolution was reached, with Fletcher reinstating Harris as NASA's deputy assistant administrator for community and human relations. From 1974 through 1992, Dr. Harriett Jenkins, the new chief of affirmative action at NASA, began the process of slowly diversifying NASA's workforce and increasing the number of female and minority candidates.

Though few in number, women and minorities made important contributions to the Space Shuttle Program as NASA struggled with issues of race and sex. Dottie Lee, one of the few women engineers at Johnson Space Center and the subsystem manager for Aerothermodynamics, encouraged engineers to use a French curve design for the spacecraft's nose, which is now affectionately called "Dottie's nose." NASA named Isaac Gillam as head of Shuttle Operations at the Dryden Flight Research Center, where he coordinated the Approach and Landing Tests. In 1978, he became the first African American to lead a NASA center. JoAnn Morgan of Kennedy Space Center served as the deputy project manager, which developed the Space Shuttle Launch Processing Systems Central Data Subsystems used for Columbia's first launch in 1981.

Astronaut Corps

Forced to diversify its workforce in the 1970s, NASA encouraged women and minorities to apply for the first class of Space Shuttle astronauts in 1976. When NASA announced the names in January of 1978, the list included six women, three African Americans, and one Japanese American, all of whom held advanced degrees. Two of the women were medical doctors, another held a PhD in engineering, and the others held PhDs in the sciences. Two of the three African Americans had earned doctorates, while the third, Frederick Gregory, held a master's degree. The only Asian member of their class, Ellison Onizuka, completed a master's degree in aerospace engineering. This was the most diverse group of astronauts NASA had ever selected and it illustrated the sea change brought about within the Astronaut Corps by 1978. From then on, all astronaut

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Astronaut Michael Anderson (Lieutenant Colonel, US Air Force) flew on STS-89 (1998) and then on the ill-fated Columbia.

The objectives are to inspire students to prepare for college by taking more advanced mathematics courses along with improved problem-solving skills, and learning more about the fields of engineering. Parents are involved in helping plan their child's academic career in science, mathematics, or engineering.

Students participate in a 3-week training program each summer. Alabama A&M School of Engineering faculty and NASA employees serve as students' leaders and mentors. At the end, the students present their engineering and mathematics projects. From these activities, the curriculum and management design are disseminated to other minority-serving institutions.

Michael P. Anderson Project students Alecea Kendall, a tenth-grade New Century Technology student, and Hilton Crenshaw, a tenth-grade Lee High student, work as a team to assemble their LEGO NXT Mindstorm robot.

Long Distance Calls from Space

Students and teachers have friends in high places, and they often chat with them during shuttle missions. In November 1983, Astronaut Owen Garriott carried a handheld ham radio aboard Space Shuttle Columbia. The ham radio contacts evolved into the Space Shuttle Amateur Radio Experiment, which provided students with the opportunity to talk with shuttle astronauts while they orbited the Earth. Ham radio contacts moved from shuttle to the International Space Station, and this activity has transitioned to amateur radio on board the International Space Station. In addition to ham radio contacts, students and teachers participated in live in-flight education downlinks that included live video of the astronauts on orbit. The 20-minute downlinks provided a unique learning opportunity for students to exchange ideas with astronauts and watch demonstrations in a microgravity environment. Ham radio contacts and in-flight education downlinks allowed over 6 million students to experience a personal connection with space exploration.

Astronauts Speak to Students Through Direct Downlink

The STS-118 (2007) crew answering a student's question.

Elementary school student asking the crew a question.

Student watching the downlink for STS-118.

Students participated in in-flight education downlinks that included live video of the astronauts on orbit. Students asked questions and exchanged ideas with astronauts.

Engineering Innovations

form the contours of these structural components. NASA made an exhaustive effort to ensure that these materials would operate over a large spectrum of environments during launch, ascent, on-orbit operations, re-entry, and landing.

Environments

During re-entry, the orbiter's external surface reached extreme temperatures—up to 1,648°C (3,000°F). The thermal protection system was designed to provide a smooth, aerodynamic surface while protecting the underlying metal structure from excessive temperature. The loads endured by the system included launch acoustics, aerodynamic loading and associated structural deflections, and on-orbit temperature variations, as well as natural environments such as salt fog, wind, and rain. In addition, the thermal protection system had to resist pyrotechnic shock loads as the orbiter separated from the ET.

The thermal protection system consisted of various materials applied externally to the outer structural skin of the orbiter to passively maintain the skin within acceptable temperatures, primarily during the re-entry phase of the mission. During this phase, the thermal protection system materials protected the orbiter's outer skin from exceeding temperatures of 176°C (350°F). In addition, they were reusable for 100 missions with refurbishment and maintenance. These materials performed in temperatures that ranged from -156°C (-250°F) in the cold soak of space to re-entry temperatures that reached nearly 1,648°C (3,000°F). The thermal protection system also withstood the forces induced by deflections of the orbiter airframe as it responded to various external environments.

At the vehicle surface, a boundary layer developed and was designed to be laminar; however, small gaps and discontinuities on the vehicle surface could cause the flow to transition from laminar to turbulent, thus increasing the overall heating. Therefore, tight fabrication and assembly tolerances were required of the thermal protection system to prevent a transition to turbulent flow early in the flight when heating was at its highest.

Requirements for the thermal protection system extended beyond the nominal trajectories. For abort scenarios, the systems had to continue to perform in drastically different environments. These scenarios included: Return-to-Launch Site; Abort Once Around; Transatlantic Abort Landing; and others. Many of these abort scenarios increased heat load to the vehicle and pushed the capabilities of the materials to their limits.

Thermal Protection System Materials

Several types of thermal protection system materials were used on the orbiter. Such materials included: tiles; advanced flexible reusable surface insulation; reinforced carbon-carbon; and flexible reusable surface insulation. All of these materials used high emissivity coatings to ensure the maximum rejection of incoming convective heat through radiative heat transfer. Selection was based on the temperature on the vehicle. In areas where temperatures fell below approximately 1,260°C (2,300°F), NASA used rigid silica tiles or fibrous insulation. At temperatures above that point, the agency used reinforced carbon-carbon.

Orbiter Tile Placement System Configuration

High-temperature Reusable Surface Insulation Tile Attachment System

Tiles

The background to the shuttle's tiles lay in work dating to the early 1960s at Lockheed Missiles and Space Company (Bethesda, Maryland). A Lockheed patent disclosure of December 1960 gave the first presentation of a reusable insulation made of ceramic fibers for use as a re-entry vehicle heat shield. In a phased shuttle thermal protection system development effort, ablatives and hot structures were the early competitors. However, tight cost constraints and a strong desire to build the orbiter with an aluminum airframe pointed toward an innovative lightweight and reusable insulation material that could be bonded directly to the airframe skin.

NASA used two categories of thermal protection system tiles on the orbiter—low- and high-temperature reusable surface insulation. Surface coating constituted the primary difference between these two categories. High-temperature reusable surface insulation tiles used a black borosilicate glass coating, which had an emittance value greater than 0.8 and covered areas of the vehicle in which temperatures reached up to 1,260°C (2,300°F). Low-temperature reusable surface insulation tiles contained a white coating with the proper optical properties needed to maintain the appropriate on-orbit temperatures for vehicle thermal control purposes. The low-temperature reusable surface insulation tiles covered areas of the vehicle in which temperatures reached up to 649°C (1,200°F).

The orbiter used several different types of tiles, depending on the thermal requirements. Over the years of the program, the tile composition changed with NASA's improved understanding of the thermal conditions. The majority of these tiles, manufactured by Lockheed International, were LI900 and LI2200. Fibrous Refractory Composite Insulation (FRCI-12) tiles helped reduce the overall weight, and later replaced the LI2200 tiles used around door penetrations. Alumina Enhanced Thermal Barrier (AETB-8) was used in areas where small particles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Boeing Rigidized Insulation (BRI-18). Overall, the major improvements included reduction of weight, vulnerability to orbital debris, and minimal thermal conductivity.

184 Engineering Innovations

Engineering Innovations 185

Major Science Discoveries

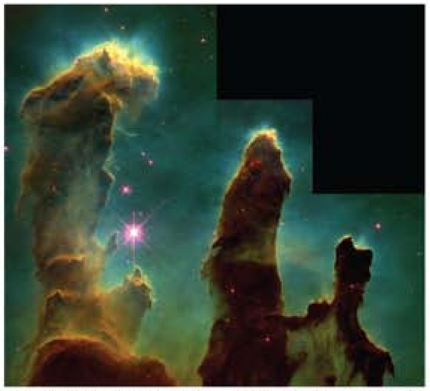
New Results After Servicing Mission 1

Immediately, NASA obtained impressive results. For example, Wide Field Planetary Camera 2 images of the Orion Nebula region resolved tiny areas of compact dust around newly formed stars. These protoplanetary disks, sometimes called *proplyds*, were the first hint that Hubble would contribute in a significant way to the studies of the formation of extrasolar planetary systems. In another observation, Hubble detected a faint galaxy around a luminous quasar (short for quasi-stellar object), suggesting that luminous quasars and galaxies were fundamentally linked. In our own galaxy, the core of an extremely dense ancient cluster of stars—the globular cluster 47 Tucanae—was resolved, demonstrating definitively to the skeptical scientific community that individual stars in crowded fields could be distinguished with the superb imaging power of Hubble.

Shoemaker-Levy

Early Hubble observations of solar system objects included the spectacular crash of Comet Shoemaker-Levy 9 into Jupiter in 1994. This event was witnessed from start to finish, from the first fragment impact to the aftermath on the Jovian atmosphere. Images were also taken in visible blue light and ultraviolet light to determine the depth of the impacts and the nature of Jupiter's atmospheric composition.

Color image of Jupiter showing the affect of the several impacts of Comet Shoemaker-Levy 9 after its multiple fragments impacted the planet in 1994.



Gas pillars in the Eagle Nebula: Pillars of Creation in star-forming region captured by the Wide Field Planetary Camera 2 in 1995. The region is trillions and trillions of miles away in the constellation Serpens. The tallest pillar is 4 light-years long and the colors show emissions from different atoms.

Pillars of Creation

The famous "Pillars of Creation" image of the Eagle Nebula captured the public imagination and contributed to the understanding of star formation processes. The images captured in 1995 with Wide Field Planetary Camera 2 showed narrow features protruding from columns of cold gas and dust. Inside the gaseous "towers," interstellar material collapses to form young stars. These new hot stars then heat and ionize the gas and blow it away from the formation sites. The dramatic scene, published in newspapers far and wide, began to redeem the public reputation of Hubble.

Existence of Supermassive Black Holes

From ground-based data, scientists knew that galaxies exhibit jets, and powerful radio emission that extends well beyond their optical periphery. Huge x-ray emissions and spectroscopic observations of galaxies suggested that some of these objects might contain a large amount of mass near their centers. Even Wide Field Planetary Camera 2 observations of the innards of several galaxies suggested that black holes might be hidden there. However, it was the observation of the giant elliptical galaxy M87 with the Faint Object Spectrograph that conclusively demonstrated that supermassive black holes exist in large galaxies. This was the turning point in black hole studies, with spectroscopy being the powerful diagnostic tool astronomers could use to begin the Hubble census of these exotic objects.

Building Blocks of Early Galaxies

One of the planned goals for Hubble research was to understand the nature of the universe and look back in time to the earliest forming galaxies. In December 1995, 2 years after the first servicing mission, Hubble's Wide Field Planetary Camera 2 was pointed at a field in Ursa Major for 10 days, accumulating 342 exposures. The final image—the Hubble Deep Field—was, at the time, the deepest astronomical image ever acquired. The field probes deep into the universe and contains over 1,500 galaxies at various distances.

After the Hubble Deep Field data were produced, telescopes were pointed at the same part of the sky to obtain data in every conceivable way. Besides bolstering the idea that galaxies form from building blocks of smaller components that are irregularly shaped and that the rate of star and galaxy formation was much higher in the past, analysis of the data pushed the observable universe back to approximately 12 billion years. Papers written on Hubble Deep Field data alone number in the hundreds and document the new understanding of cosmological and astrophysical phenomena.

The immediate release of Hubble Deep Field data represented a watershed in astronomical research as well. A new method was born for concentrating astronomical facilities and the collective brainpower of the scientific community on a specific research problem. Thus, the Hubble Deep Field represents not only a leap forward in scientific understanding of the universe, but a significant alteration in the way astronomy was conducted.

Edward Weiler, PhD
Chief scientist for the Hubble Space Telescope (1979–1998)
NASA associate administrator, Science Mission Directorate

"It's fair to say that Hubble, today, would be a piece of orbiting space debris if it hadn't been for the Space Shuttle Program. If Hubble had been launched on an expendable launch vehicle, we would have discovered the optical problem, yet been unable to fix it. Hubble would have been known as one of the great American scientific disasters of our time. Hubble's redemption is due to the Space Shuttle Program and, most importantly, to the astronauts who flew the shuttle and did things (in repairing Hubble) that we never thought could be done in space. Hubble became a symbol of excellence in technology and science, and the shuttle made that happen.

"I've spent 34 years on Hubble in one way or another. I was on top of Mount Everest at the launch, with all of us astronomers who had never done an interview. I was on the Today Show and Nightline on the same day. I experienced the ecstasy in April of 1990, to the bottom of the Dead Sea 2 months later when a spherical aberration was detected in the Hubble. In our hearts, we knew we could fix it. We promised the press we would fix it by December of 1993, and nobody believed us. Then, on December 20, 1993, we saw the first image come back. It was spectacular. It was fixed. And the rest is history. We went from the bottom of the Dead Sea back to the top of Mount Everest and beyond…we were elated!"

Subsequent Servicing Missions

Servicing Mission 2

By the end of 1996, Hubble was a productive scientific tool, with instruments for optical and ultraviolet astronomy. During the second servicing mission, in February 1997, the STS-82 crew installed two new scientific instruments: the Near Infrared Camera and Multi-Object Spectrometer, extending Hubble's capabilities to the infrared; and the Space Telescope Imaging Spectrograph, offering ultraviolet spectroscopic capability. Astronomers now expanded their research to probe astrophysical phenomena using the excellent imaging performance of Hubble coupled with new capability over a larger range of wavelengths.

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"…to review and provide recommendations to the Executive Editor on the contents and the final manuscript…"

Wayne Hale, Chair of Board

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